



Air-Rain System-Concept and Numerical Assessment on Its Ability Against the Spread of Chemical Agents in Large Space Public Buildings

Ning Chen^{1,a}, Janusz Kozinski^{2,b}

¹*School of Electric Power Engineer, China University of Mining & Technology
Xuzhou Jiangsu Prov., P.R. China (221116)*

²*Faculty of Science & Engineering, York University, Toronto, ON, Canada (M3J 1P3)*

^a*e-mail: chenning@cumt.edu.cn*, ^b*e-mail: janusz.kozinski@yorku.ca*

Abstract

The Air-Rain system is a new immune building approach to protect the indoor air in Large Space Public Buildings (LSPBs) from the airborne transmission of harmful chemical agents. A uniform, downward air flow is employed in this system in order to constrain the spread of both bio-particles and chemical agents. The numerical research with an experimentally tested model on Air-Rain system found its air ventilation with a speed of 0.02m/s can indeed constrain the spread of chemical agents in LSPBs and its safety is higher than that of Displacement Ventilation and Hybrid Ventilation in LSPBs.

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Keyword: Immune building; indoor air; HVAC system; CFD

1. Introduction

Chemical and/or biologic criminal or casualty acts are ongoing threat to the indoor air in Large Space Public Buildings (LSPBs). LSPBs can be defined as the public buildings with one or more large space halls inside, such as air-port, subway platform, supermarket, department store, waiting hall of a central hospital, etc. They are closely related with our daily lives and the chemical/biological situation of the indoor air in these buildings is essential to the public health and security.

Immune Building technology [1, 2] is one of the good answers against the chemical/biological harm to buildings, but it won't be so efficient in LSPBs. Most designs of immune buildings in the world are based on the theory of "early detecting and response" [3, 4 and 5]. Chemical and bio-sensors are placed in the HVAC system of a building for an early detecting/warning purpose. Once the dangerous agents are detected, the systems will response with an alarm or certain neutralization methods. To ensure a stable detection, many expensive bio/chemical sensors must be laid into an array with enough density in the LSPBs. This will lead to an extremely high expense to HVAC system. On the other hand, even though the

harmful agents can be detected, how to neutralize them is still a problem, because the harmful agents can flow anywhere with the ventilation, but it's impossible to amount the air-cleaning machines everywhere in the LSPBs.

2.The Concept of Air-Rain System

To solve the former problems, a system named as “Air-Rain” is developed. The concept of Air-Rain system can be explained more detail in Figure. 1. The cleaned ventilation air flows into the ceiling, separated into uniform down-flow streams by perforated plate there, and then, falls, like the rain, into the holes on the floor. The airborne transmission of respiratory bacteria/virus breathed out from a man is pressed down into floor. The possibility of infection to others, say, the lady in Figure1, will be sharply decreased then. In addition, this system is also effective to indoor chemical release (from terrorists or by casualty). The released chemical agent in the flow field will be blown into floor but not to personnel's nose or mouth.

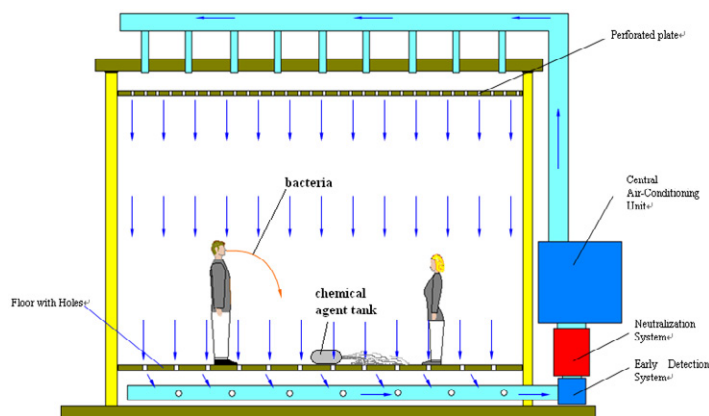


Figure 1. The Concept of Air-Rain System

The air flowed into the floor will be gathered into the air-return duct underneath the floor first, which connects with early detection system and central neutralization system. Once any harmful agents are detected, it will be decontaminated in neutralization system. Finally, clean air is sent into central air-conditioning unit for recycling. The constraining of the spread of harmful agents within indoor air is mainly based on fluid dynamic effect but not the expensive sensors. The cost of the immune building system will be decreased then.

In this paper, CFD calculations are conducted to assess the effectiveness of the Air-Rain system against the spread of chemical agents in the indoor air. The numerical simulation also covers other ventilation modes, such as displacement ventilation, as the comparison with Air-Rain system.

3.The Numerical Model of the Air-Rain Research

3.1.Physical Model of Air-Rain System

The physical model of the simulation is based on an $8 \times 8 \times 5$ meters hall. There is a model of a man in the middle of the hall, which is simplified into an elliptical cylinder. At the mouth height of the “man”, a hole with a diameter of 30mm is opened to simulate the breath of the man. Many air-return ducts with the diameter of 100mm are connected on the floor with a distance of 1 meter.

Considering the symmetry, the whole model is cut through the middle of the man into two halves. Only one half of the volume is considered as the control volume for sake of saving the calculation source. That is the space for numerical calculation is $8 \times 4 \times 5$ meters

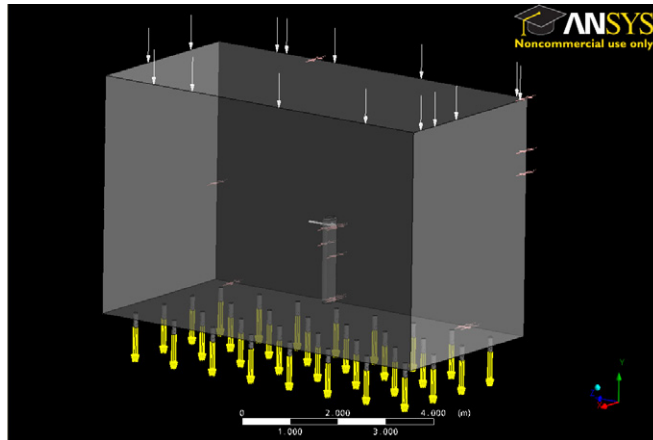


Figure 2. The Physical Model of the Air-Rain Research

3.2. The Mathematic Model

Considering the molecules of chemical agents are much smaller than the bio-particles, the spread of those molecules are much easier than that of the particles. In this sense, if the Air-Rain system can effectively constrain the spread of chemical agent, it should be functional to biological particles. Therefore, Multi-Component flow equations should be employed in the numerical research for Air-Rain system. Acetone, a typical evaporative chemical agent, is employed as simulant [6].

It is considered to be three-dimensional, thermal, incompressible, steady, turbulent, and multi-component flow in the Air-Rain system.

The mass, momentum and energy conservation equations [7] can be written in a Cartesian coordinate system as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \quad (1)$$

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = \mathbf{B} - \nabla P + \frac{2}{3} \rho \mathbf{k} + \frac{2}{3} \mu_t \nabla \cdot \mathbf{U} + \nabla \cdot \{ \mu_{eff} [\nabla \mathbf{U} + (\nabla \mathbf{U})^T] \} \quad (2)$$

$$\frac{\partial \rho h_{tot}}{\partial t} + \nabla \cdot (\rho \mathbf{U} h_{tot}) = \nabla \cdot (\lambda \nabla T - \rho \mathbf{u} h) + \nabla \cdot (\mathbf{U} \cdot \boldsymbol{\tau}) + S_E \quad (3)$$

Where: \mathbf{B} is the sum of the body forces; k is the turbulent kinetic energy; μ_{eff} is the Effective Viscosity.

The mean Total Enthalpy is given by: $h_{tot} = h + \frac{1}{2} U^2 + k$

Considering the Reynolds number in most of the control volume is low, the $k-\omega$ model [8] was employed to describe the turbulent flow, because one of the advantages of the $k-\omega$ formulation is the near wall treatment for low-Reynolds number computations where it is more accurate and more robust. The equations are:

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{U} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \beta' \rho k \omega \quad (4)$$

$$\frac{\partial (\rho \omega)}{\partial t} + \nabla \cdot (\rho \mathbf{U} \omega) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \nabla \omega \right] + \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 \quad (5)$$

If the sub i, j respectively represent the component and the vector direction, a general convection-diffusion equation [9] of the form common to equations can be solved for each of the other dependent variables in the fluid flow calculation:

$$\frac{\partial(\bar{\rho}Y_i)}{\partial t} + \frac{\partial(\bar{\rho}UY_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\Gamma_{i,eff} \frac{\partial Y_i}{\partial x_j} \right) + S_i \quad (6)$$

$$\sum_{i=A,B}^N Y_i = 1 \quad (7)$$

The accuracy of the above numerical model has been verified in a ventilation experimental platform in the University of Saskatchewan, Canada. The platform can simulate different ventilation mode in a three-room, one-corridor model. A chemical agent mixer is connected with the middle room to simulate the chemical pollution in the building. A lab-level PID was amounted to sample the air inside the building at different points. The error between numerical result and experimental data is less than 6%.

3.3. The Boundary Conditions

The Air-Rain model is considered working within HVAC system. The boundary conditions of the air flow from the ceiling are set as: Downward velocity: 0.02 m/s, Temperature: 22 °C. The air speed is referred from that of displacement ventilation [10]. The surface of the man is set at 26 °C (considered dressing-up).

Considering the floor release, no matter from terrorist's chemical attack or casualty spill, is the most common way of indoor chemical pollution, there is a hole (20mm in diameter) on the sidewall as toxic gas inlet with an inlet velocity of 5m/s to simulate the release of the harmful gas near the floor.

The walls and the floor are set as adiabatic, none-slip solid surface. Symmetric boundary condition is set to the cut surface discussed before.

All the ends of air-return duct connected with the floor are set with outlet boundary conditions.

4. The Analysis of the Numerical Result

4.1. Comparison between Air-Rain and Displacement Ventilation

The Air-Rain and displacement ventilation can be a pair of competitors with each other, because their air flow is similar and the only difference is the flow direction.

The numerical result of floor release of acetone in Air-Rain and displacement ventilation are (figure 3) shown separately in figure 3 and figure 4. The upward air speed in displacement ventilation is also 0.02m/s.

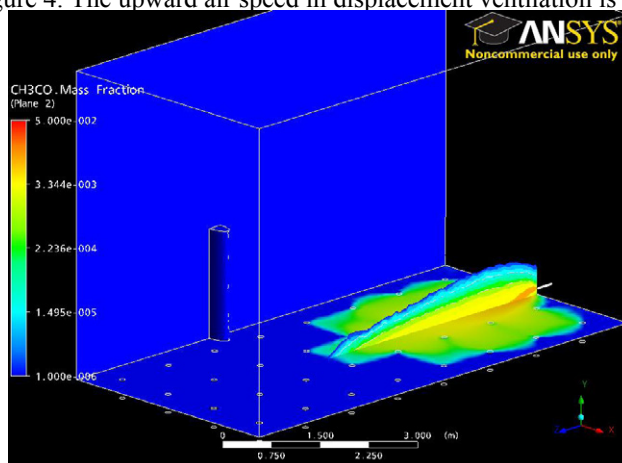


Figure 3. Acetone spreaded in Air-Rain flow

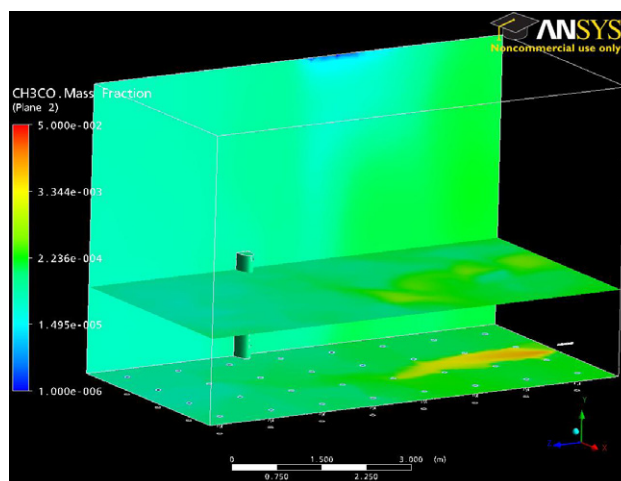


Figure 4. Acetone spreaded in displacement ventilation flow

There is a horizontal plane in figure 4 with a height of the 1.6m, which is the common height near the people's mouth and nose. Comparing with the large area of contamination in displacement ventilation, the mass fraction of acetone near the "man's" breath height in Air-Rain is zero. It can be concluded that the chemical safety of Air-Rain system is higher than that of displacement ventilation in LSPBs during floor release.

The chemical floor release in hybrid ventilation that is popular in HVAC system was not considered in the CFD calculation, because this release was proved extremely fatal, e.g., the infamous *Sarin* attack in the Tokyo subway in 1995.

4.2. Spill near the air-supplying outlet in LSPBs

All ventilation systems in LSPBs are fragile to chemical spill near its air-supplying outlet, because the harmful agent will mix with the supplied air and be blown to all places in a building.

In the situation of displacement ventilation, if certain volatile chemical spills on the floor and flows into the vent hole on the floor, it will evaporate in the air distribution layer under the floor, then spread, and finally be blown back into the building. Obviously, people inside the building are easy to be hurt by the chemical agent.

In the case of Air-Rain, its air supplier is near the ceiling but accidental spill often happens on the floor. This design can effectively decrease the possibility of people being hurt by chemical release in LSPBs.

It's also possible to attack the air supplier of Air-Rain system on purpose, say, a chemical attack from the terrorist. However, the attackers need to climb onto the ceiling first. This action is more easily perceived by the people or safe guard system inside the LSPBs so that it could make the terrorists give up their attack.

4.3. Vertical jet of chemical agent against Air-Rain

Vertical jet could be fatal to Air-Rain ventilation. The jet can be from chemical tank leakage or man-made attack. If the upper flow of the chemical agents jet reach or close to the ceiling, they could mix with the air, be blown down again and do harm to the people inside the building.

To assess the harmfulness of the vertical chemical jet to Air-Rain, 2 numerical models was studied. In the first model the speed of the vertical jet is 2m/s and in the second, 20m/s.

The calculated result (figure 7) shows that the chemical pollution from vertical jet to the indoor air is very limited in Air-Rain flow. The diameters of the polluted area under both jet speeds are less than 3.5m.

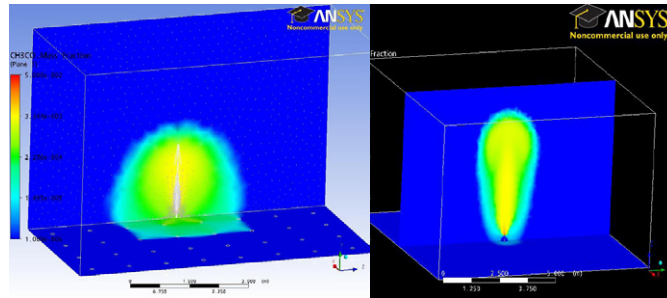


Figure 5. Mass fraction distribution of vertical jet acetone in Air-Rain flow (Left: jet speed 2m/s; Right: jet speed 20m/s)

5. Conclusion

Air Rain system is a new immune building technique to protect the indoor air in Large Space Public Buildings from the pollution of chemical agents or airborne transmission of respiratory diseases. A uniform downward air flow in this system is employed to constrain the spread of bio-particles or chemical agents. The numerical research with an experimentally tested model on Air Rain system concludes:

(1) Numerical research on an experimentally tested model of the Air-Rain system shows that a downward flow of 0.02 m/s can indeed constrain the spread of chemical agents;

(2) The use of Air-Rain flow, following a floor chemical release, can effectively inhibit chemical agents from breathed in by people in LSPBs, but the alternative displacement ventilation and hybrid ventilation flows cannot;

(3) It may be possible to design specific man-made chemical attacks against an Air-Rain system, such attacks will be difficult to conduct or probably will not be that effective.

6. Acknowledgment

This research is supported the Natural Sciences & Engineering Research Council of Canada via a Strategic Project entitled “Immune Buildings: Development of eWAR Systems.” Prof. Ning Chen would like to thank China Scholarship Council for its financial support for his research stay in Canada.

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